

WHITEPAPER

**HIGH-FIDELITY NUMERICAL MODELING OF SPARK
PLUG EROSION WITH VIZSPARK**

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Overview

Spark-plug erosion is critical in determining the overall efficiency of a spark ignition engine. Over its lifetime, a spark plug is subject to millions of firings. Each spark event results in material erosion due to several mechanisms such as melting, vaporization, sputtering, and oxidation. With electrode wear, the inter-electrode spacing increases and a larger voltage difference is required to initiate the spark. The probability of engine misfire also increases with electrode erosion. Once a critical gap is reached, the energy in the ignition coil is no longer sufficient to cause a spark breakdown and the spark plug must be replaced. Due to the long relevant timescales over which erosion occurs and the difficulty of analyzing the spark plug environment during operation, determining spark plug lifetime requires time consuming and expensive field testing. A numerical model capable of modeling electrode erosion and deformation would be a useful alternative to supplement the design and field testing of spark plugs. VizSpark is a thermal plasma simulator capable of coupling arc physics with electrode erosion and deformation. The model includes the capability of coupling high fidelity arc physics with a model that can dynamically alter the electrode geometry of an electrode. The erosion mechanism is modeled using a phenomenological model based on energy delivered to the electrode from the arc. The electrode erosion model is validated against experimental results and a 3D electrode erosion in stationary and cross-flow conditions is performed as a demonstration.

Objective

The objective of this work is to demonstrate a model capable of coupling arc physics, erosion physics, and electrode deformation as a fully coupled modeling approach. A phenomenological model capable of modeling electrode erosion that is suitable for a plasma fluid model is presented along with validation. A demonstration of how the model can be used to predict lifetime using a realistic 3D spark plug model in cross-flow conditions is demonstrated.

Erosion Model Validation Simulation Setup

The erosion model is based on previous work described in the literature^[1] and quantifies the electrode erosion as a function of the incident energy flux to the electrode through a proportionality factor called the K-factor.



Figure 1: Domain and mesh for the pin to plane arc simulation. The mesh consists of 9,664 cells. The anode (top electrode) is conical in shape with base diameter of 0.6 mm, and the cathode (bottom electrode) is cylindrical (diameter 1 mm).

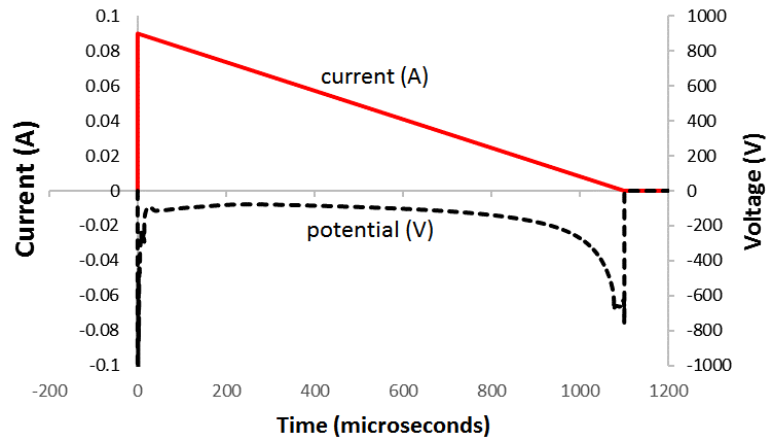


Figure 2: Domain and mesh for the pin to plane arc simulation. The mesh consists of 9,664 cells. The anode (top electrode) is conical in shape with base diameter of 0.6 mm, and the cathode (bottom electrode) is cylindrical (diameter 1 mm).

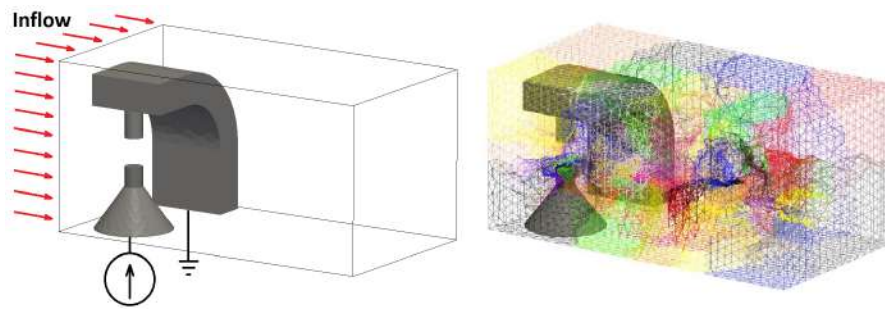


Figure 3: Domain (left) and numerical mesh (right) for 3-D sparkplug with constant current power source and grounded L-jacket. The boundary where inflow is applied is shown with red arrows. The numerical mesh consisting of 328,287 cells split amongst 40 computing processors.

This K-factor is calibrated against experiments from Refs. 1 and 2 for tungsten (W), iridium (Ir), nickel (Ni), platinum (Pt), tin (Sn) and silver (Ag). The inputs to the model are geometry, electrical parameters and the predicted outputs are volume of eroded electrode and the total spark discharge energy. The ablation K-factor for air from Ref. 2 is used in the our simulations which uses input electrical power (surface voltage times surface current) as the dependent energy.

The geometry and mesh shown in Figure 1 consists of an axisymmetric pin-to-plane spark plug, with a cylindrical cathode (diameter 1 mm), and a conical anode (max diameter 0.6 mm). The mesh consists of variable sized triangles across the entire domain. At the cathode boundary, a fixed current profile is applied with a peak amplitude of 0.9 A that decreases linearly to 0 over 1.1 milliseconds (see Figure 2). The anode boundary is treated as electrically ground. For the outer boundaries, a symmetry condition is applied such that there are no far-field gradients for flow or electric field variables.

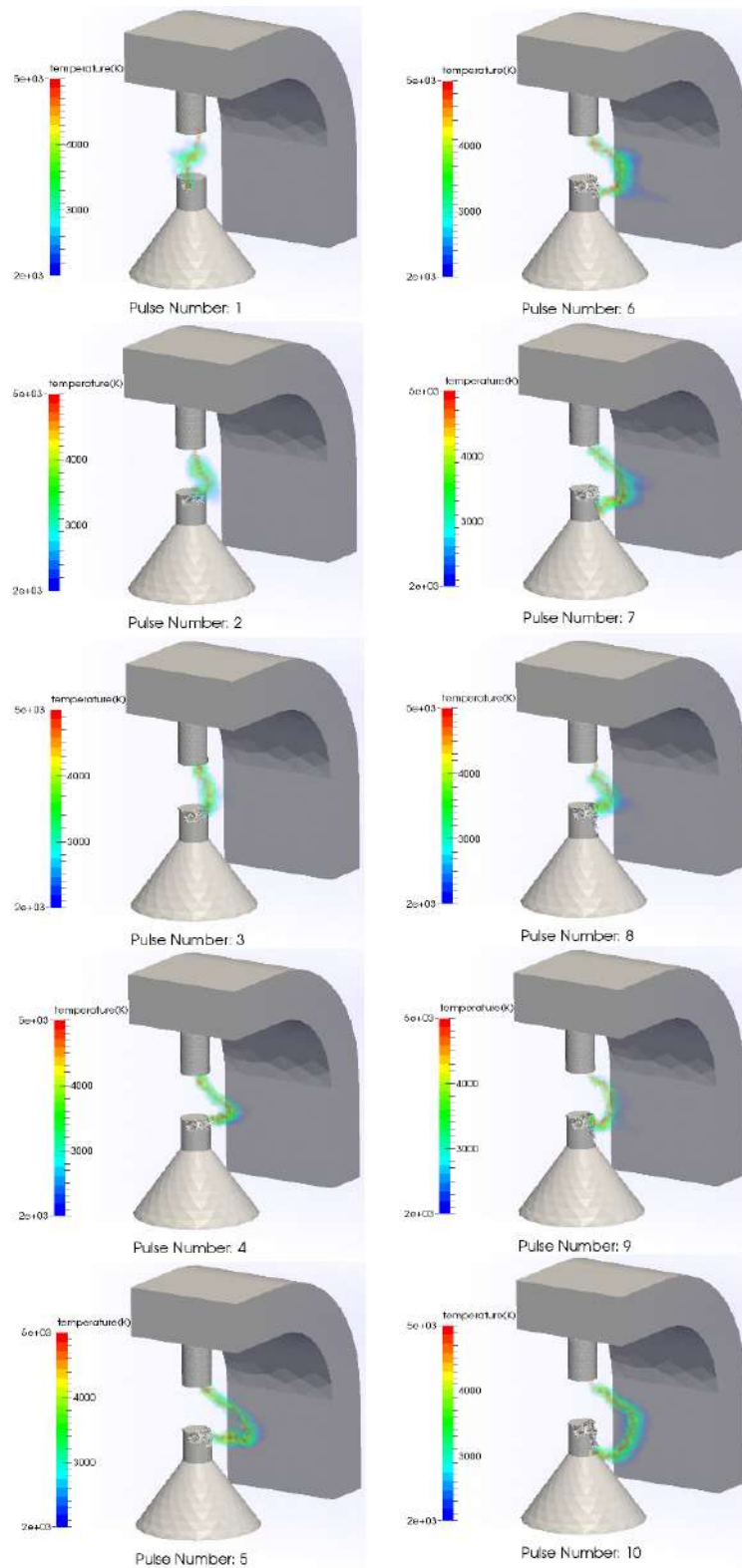


Figure 4: Time transients of the arc channel and electrodes for the sparkplug in 8 m/s crossflow at start of each simulated pulse (10 pulses total).

3-D Spark Plug Erosion

Spark erosion occurs over many millions of spark events. Simulating millions of sparking events at high fidelity is numerically infeasible. We assume the approximation that the erosion that occurs over long-time scales and millions of firings can be approximately captured with only a few high-fidelity simulations and a multiplier on the rate of ablation at the arc root surface. A typical spark duration for a car ignition system is of the order of 1 millisecond and for inductive ignition systems the current profile will often have a sawtooth waveform.^[3] In this work the electrical input boundary condition is specified as a sequence of 100 microsecond sawtooth current wave form pulses with an initial peak of 50 mA which then decrease linearly to zero as in.

A numerical mesh consisting of 328,287 tetrahedral cells is imposed on the problem domain and shown in Figure 3. A domain decomposition approach is utilized, where the numerical mesh is split equally amongst multiple processors and solved in parallel to reduce the computational solve time.

For both flow and no-flow simulations, 10 numerical pulses of 0.1 milliseconds are applied. Each pulse consists of applying an input current with peak current of 50 mA which then decreases linearly to zero (sawtooth pulsing).

The rate at which ablation takes place along the electrode surface can be accelerated beyond the timescale of the arc event by applying a multiplicative factor to the surface erosion rate calculated by the surface erosion model. We apply an erosion multiplicative factor of 10^6 such that each simulated pulse removes the mass that approximately 10^6 real sparking events would remove.

Each simulated pulse is separated by 20 microseconds of zero-current off time. During the pulse off-time, the arc channel quenches such that each new pulse is applied to a cool arc channel and ensuring that each simulated spark is independent of the prior simulated arc.

8 m/s Crossflow

The results for the simulation with an 8 m/s cross-flow are presented first. Figure 4 presents time snapshots of the arc temperature and the electrode surface topology at the end of each simulated pulse. One can see the arc stretch due to the cross-flow in each of the images and the steady removal of cells on the powered cathode as the simulation evolves with time.

Figure 5 presents the current applied and voltage measured at the base (bottom side) of the powered electrode as function of pulse. The current was applied in a series of saw-tooth pulses and the voltage on the electrode is obtained self-consistently by the solver. Observe that initially, there is a high voltage spike at the start of each current pulse indicating gas breakdown. Note also, the increase in voltage as the arc stretches with the cross-flow during each pulse. Furthermore, as the electrode surface erodes and the gap distance increases, the arc voltages required to maintain the arc change. In general, the voltages increase as the surface erodes.

No-Crossflow

The same simulation configuration is repeated with no-crossflow to determine the impact of flow on spark life time.

The voltage and current transients as a function of individual pulses are shown in Figure 5. The same saw-tooth current profile that was used for the cross-flow case is used as a boundary condition input to the cathode. The voltage profile displays voltage peaks during breakdown and a slow increase in the voltage. Compared

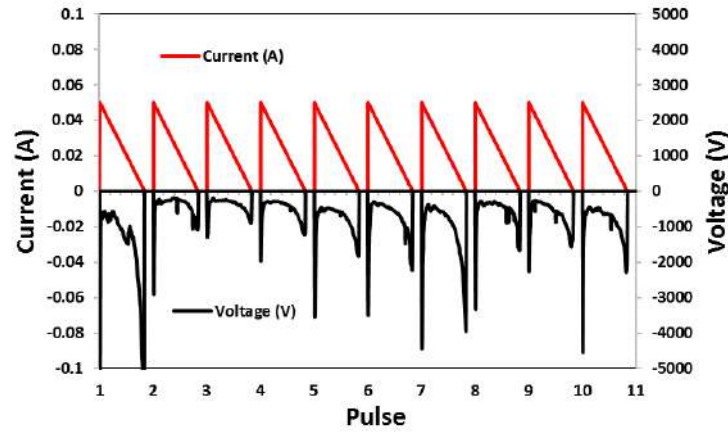


Figure 5: Electric current (top) and voltage (bottom) transients as function of applied pulse for the simulation with cross-flow.

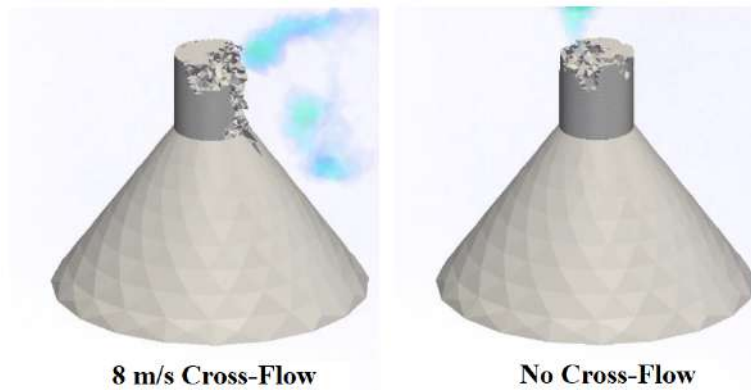


Figure 6: Erosion profiles for sparkplug cathode after 10 simulated pulses for the case with 8 m/s crossflow (left) and case with no cross- flow (right).

to the case with cross-flow (Figure 5), the peak voltages are lower and the magnitude of voltage increase over each pulse duration is lower. The lower voltages indicate that the spark channel resistance in the no-flow case is lower compared to the cross-flow case. This makes sense intuitively as the channel length and hence channel resistance is lower when there is now cross-flow compared to the case when there is cross-flow and arc stretch.

The erosion profile of the powered electrode (cathode) for the case with and without cross-flow are compared in Figure 6. The cross-flow case shows preferential wear on the downwind side of the electrode.

The eroded mass of the powered electrode (cathode) for 8 m/s cross-flow and stationary flow compared in Figure 7. Two trends are noticeable: the first is that during breakdown at the start of each pulse there is more mass removal then during the arc phase. The second is that the net eroded mass is higher for the case of cross-flow. The observation of increased material erosion for the case of cross-flow can be explained through the following argument: the supplied current for both simulations is the same yet cross-flow stretches the arc. The arc channel can be thought of as a resistive element, hence a longer stretched arc will have more electrical resistance then a non-stretched arc. More energy is required to maintain a stretched arc compared to a stationary arc and because electrode erosion is a function of electrical energy deposition, more energy is transferred to the electrodes which leads to more erosion.

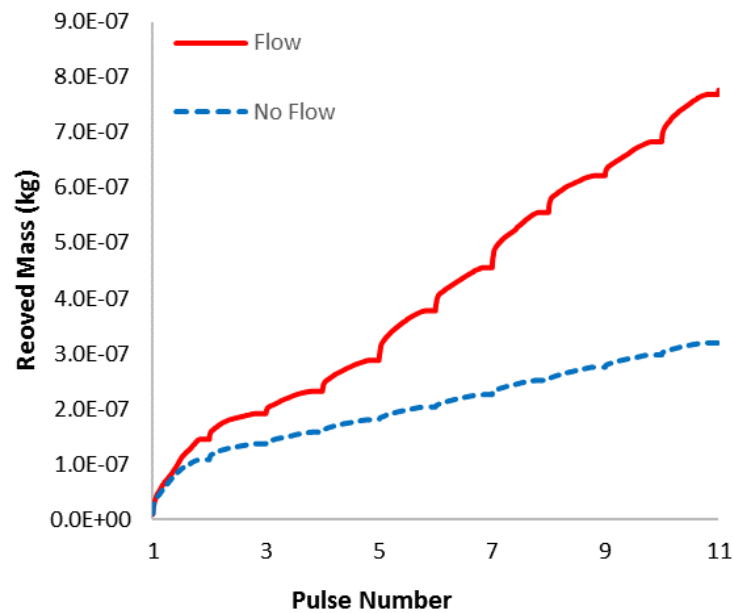


Figure 7: Eroded electrode (cathode) mass as a function of simulated pulses. The eroded mass for stationary flow is shown with the dashed line (blue). Eroded mass for the cross-flow case is shown with the solid line (red).

References

- ^[1] L. A. F. Soldara, and F. Mucklich *Zeitschrift fur Metallkunde*, vol. 95, no. 2, pp. 102–108, 2004.
- ^[2] F. A. Soldara, F. T. Mucklich, K. Hrastnik, and T. Kaiser, “Description of the discharge process in spark plugs and its correlation with the electrode erosion patterns,” *IEEE Transactions on Vehicular Technology*, vol. 53, pp. 1257–1265, July 2004.
- ^[3] T. Shiraishi, A. Teraji, and Y. Moriyoshi, “The effects of ignition environment and discharge waveform characteristics on spark channel formation and relationship between the discharge parameters and the egr combustion limit,” *SAE Int. J. Engines*, vol. 9, pp. 171–178, 09 2015.



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